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New Opportunities in Neutron Capture Research Using Advanced Pulsed Neutron Sources

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ABSTRACT: The extraordinary neutron intensities available from the new spallation pulsed neutron sources open up exciting opportunities for basic and applied research in neutron nuclear physics. Prospective experiments are reviewed with particular attention to those with a strong connection to capture gamma-ray spectroscopy.

1. INTRODUCTION

This Conference traces its origins to the subtopic of neutron capture gamma ray spectroscopy. Its scope in experimental technique has been broadened and enriched over the years through the addition of techniques such as proton capture, heavy-ion-induced transitions, photonuclear methods, inelastic electron scattering, etc. The primary purpose of this talk is to point out new opportunities in the original field of neutron capture associated with powerful new spallation neutron sources. These sources are arriving primarily owing to their promise for condensed matter physics studies. Use of these sources by nuclear physicists has been modest up to now, but hopefully this talk will stimulate more neutron nuclear research to the benefit of both the condensed matter and nuclear research communities.

2. SPALLATION NEUTRON SOURCES

Condensed matter research using pulsed neutrons can be effectively conducted using a spallation source with proton energy near one GeV and a pulse width of a few tenths of a microsecond. The proton burst is produced in two stages. First protons are accelerated in an r. f. linac to an energy of at least 100 MeV. This beam is accumulated in a ring, where it may be further accelerated, and then dumped in one circuit of the ring into a heavy metal target. For a proton energy of 800 MeV, approximately 25 neutrons are produced per proton in the spallation process.

This concept is implemented [1] at Los Alamos in the Los Alamos Neutron Scattering Center (LANSCE) as shown in Fig. 1 by injecting 10% of the 800-MeV H^+ beam from LAMPF into the Proton Storage Ring (PSR) [2]. In the design objective an average current on Target 1 of 100 microamps is achieved by ejecting 0.27-microsecond wide pulses from the PSR each containing 5×10^{13} protons at the rate of 12 Hertz. The resulting neutron intensity is about 10^{15} neutrons per pulse, or an average neutron intensity of 10^{16} neutrons per second. The instantaneous neutron production rate is 4×10^{21} per second. This mode provides intense beams for neutron physics research in the 0.01 to 10,000 eV range.

In Fig. 2 the resolution is given for flight paths of 7, 50 and 250 meters. For LANSCE operation at 100 microamps we use the moderated neutron intensity formula

$$\text{flux} = 4 \times 10^{10} / EL^2 \text{ neutrons per eV per second}$$

for a 100-cm^2 sample at the neutron energy E (eV) with a flight path length of L (meters).

Intense bursts of MeV neutrons also can be produced using the same facility. Most of the time LAMPF provides 800-MeV proton beam for meson production. However it is also possible simultaneously with meson production to accelerate a smaller current of H^- beam at a point on the r. f. cycle 180 degrees in phase away from that used for H^+ acceleration. The two beams of different charge are separated at the end of the accelerator in a magnetic field. The H^- beam bypasses the storage ring and strikes a second spallation target, Target 4. Since the typical r. f. burst is only about 300 picoseconds wide, short bursts of neutrons are produced for research in the 1 to 400 MeV range. The average proton current for this mode is a few microamps achieved at a pulse rate of about 35,000 Hz. This new capability and the planned research is described in detail by Wender et al. [3]. Multiplexing in the beam transport system of Line D and appropriate neutron shielding allows simultaneous experiments at both Targets 1 and 4.

3. EV NEUTRON PHYSICS RESEARCH

The neutron nuclear physics being contemplated at LANSCE is shown in Table I. Not all of it is gamma-ray spectroscopy, not all even nuclear physics, nor do we expect to mount experiments in all of these subjects. Nevertheless it is appropriate to mention these topics in this symposium since many of you have a strong background in neutron physics and it is unlikely that much of this proposed work will get done without the involvement of scientists with the interests represented at this Conference.

Table I

Topics for eV Neutron Physics Research at Spallation Sources

- Parity Violation
- T-violation in the weak and strong forces
- Unstable nuclei: (n,p) and (n,gamma) reactions
- Neutron capture gamma-ray spectroscopy
- Ultrahigh resolution photonuclear research
- Neutron-pumped gamma-ray laser
- Neutron-induced electronic excitation
- Physics of neutron dosimetry
- Resonance neutron optics
- Resonance Neutron Radiography
- Lead slowing-down spectrometer
- Neutron-neutron scattering

Much of this work requires the use of polarized beams; before discussing the science it is therefore worthwhile to describe a new technique we are establishing for obtaining polarized neutron beams at LANSCE based on polarized ^3He . The helium is polarized by bathing a mixture of helium gas and a small amount of vaporized rubidium with polarized laser light [4]. The alkali vapor is polarized in the optical pumping process and the polarization transferred to the helium nuclei by the spin-spin interaction. We expect to achieve a high ^3He polarization in a 30 atmosphere-cm³ volume. The actual cell will have an area of area of 1 cm², a length of 4 cm, and a pressure of 8 atmospheres. It will be located at a flight path distance of 7 meters. The polarization as a function of energy is shown in Fig. 2.

This technique has the advantage over a polarized hydrogen target of little loss in neutron intensity in the polarization process, easy spin flipping simply by rotating the weak holding magnetic field by changing current in surrounding Helmholtz coils, eight-hour polarization decay time in the absence of laser pumping, no cryogenics, and no superconducting magnetic field coils. It has the disadvantage that at its present stage the beam area is small and useful polarization experiments are limited to the energy range below 30 eV. This compares with an achieved [5] 30-cm² area for polarized hydrogen and an energy range extending up to 50 keV, albeit with a neutron intensity loss of 10. Progress in the size of the polarized ^3He has moved rapidly; we may hope that another order of magnitude will be achieved in the not too distant future. Perhaps a relatively modest and inexpensive neutron polarization and spin flipping system combined with an intense spallation source will have a major impact on many aspects of neutron spectroscopy.

3.1 Parity Violation

The current most active field of neutron research requiring eV polarized beams is the study of enhanced parity violation in low energy p-wave resonances pioneered by the Dubna group [6]. They studied the transmission of neutron beams polarized along and against the neutron propagation vector k . Since the dot product $\sigma \cdot k$ does not conserve parity, parity violation will be manifested as a difference in the two transmissions in the resonance. The largest effect observed to date [6] is a 8.5% parity mixing in the 0.734 eV resonance in ^{139}La . The KEK group has repeated the experiment [7] by detecting the resonance capture gamma rays. Since the neutron width is very small compared to the capture width, the two experiments are equivalent if the gamma detector efficiency is isotropic and the detector is centered on the sample.

This experiment was performed in a third way at Los Alamos [8] at LANSCE without neutron beam polarization apparatus as shown in Fig. 3. An unpolarized neutron beam striking a thick ^{139}La sample will emerge with polarization if P-violation is present in the resonance. We detect this polarization by passing the neutrons next through a spin flipper and then through a second sample of ^{139}La . A difference in the transmission for the two spin directions indicates the presence of P-violation. We also attempted the detection of capture gamma rays from the second sample, but were foiled by bothersome backgrounds.

P-violation is a manifestation of the mixing via the weak force of the amplitude of an s-wave resonance into a neighboring p-wave resonance of the same spin [9]. Resonance capture gamma ray spectroscopy can play a role in two ways in assuring the proper conditions for interpreting the absence or presence of a P-violating effect. First it can be used to determine the spin of the p-wave resonance in accordance with established techniques. This is important since not all p-wave resonances have the proper spin to interfere with s-wave resonances. Second for

non zero spin target nuclei, a p-wave resonance will be a mixture of two channel spins $l \pm 1/2$. Only the $l-1/2$ amplitude can mix with the s-wave resonance. To extract an accurate matrix element for the parity mixing, the channel spin mixture must be determined. This mixture in the p-wave resonance can be determined by measuring the angular and polarization correlations in the capture gamma ray spectrum between states of known spin [10].

The measurements of P-violation in resonances have thus far been carried out with modest intensity neutron sources achieving a sensitivity of about 1 in 1000. The powerful spallation sources might allow sensitivities better by a factor of 1000. It might therefore be possible to extend the measurement into a higher energy range where the parity mixing is reduced allowing the measurement of matrix elements for several resonances in a single nucleus. In this way an average matrix element for the nucleus analogous to a neutron strength function can be determined. If this could be done for many nuclei across a wide mass range, the mass dependence of a parity-mixing strength function could be measured.

Remembering that parity mixing is a property of the weak force, such a study would be of great interest since it would be the first measurement of the manifestation of the weak force in many nucleon systems. To fully appreciate this point it is useful to be reminded that both the strong and the weak force are well characterized at the nucleon-nucleon level. For the strong force this knowledge does not allow one to predict the properties of many nucleon systems. Perhaps the most fundamental manifestation of the strong force first predicted and measured was the giant resonance structure in the s-wave strength function. By analogy the measurement of the average value for the P-violating matrix element for many nuclei would allow the first measurement of the manifestation of the weak force in nuclei. Presently no predictions of the trend with A for this weak interaction strength function exist. Finally it should be mentioned that the channel spin mixture need not be measured for zero-spin targets. The derivation of an accurate matrix element from the observed parity mixing is therefore greatly simplified for this class of nuclei.

3.2 T-Violation in the Weak Force

Although CP-violation was detected long ago in neutral kaon decay [10] time reversal invariance violation (T-violation) implied by CPT conservation has never been directly detected. Nor has CP- or T- violation been seen in any other system. The lack of understanding of the nature of CP-violation is a major barrier to further advances in the Standard Model. The most sensitive and extensive search to date has been for detection of an electric dipole moment of the neutron which would be an unambiguous signature for T-violation in the neutron.

The presence of P-violation in neutron resonances is a signature for the weak force. Such resonances are therefore alternative candidate nuclear systems for a sensitive search for T-violation. The T-violation will be manifested in an amplitude containing a term of the form $(\sigma \cdot k \times I)$ where σ is the neutron spin, I the spin of the target nucleus, and k the neutron momentum vector. The experiment requires the polarization of the neutron beam and the target nucleus normal to one another and also both normal to k . T-violation would be manifested as a change in the transmission at resonance when the neutron spin direction is changed by 180 degrees.

The experiment is significantly complicated by the existence of pseudo-magnetic rotation [12]. It is a consequence of the different index of refraction (and therefore velocity) for the two different scattering amplitudes $J = I \pm 1/2$ for polarized neutrons in a polarized medium. The neutron spin is caused to rotate around the target polarization vector thus spoiling the experiment. This effect can be canceled

in principal by mixing the target of interest with other material with scattering length of the opposite sign.

It appears that the spallation sources might give a statistical accuracy for detecting a difference in the transmission of the two polarizations at resonance of 10^{-6} . For a resonance exhibiting P- violation (weak force fraction) of 10^{-1} , a T- violation sensitivity of 10^{-5} might be obtained [13]. According to Herczeg [14] sensitivity in the range of 10^{-3} and below is useful for testing various proposed extensions of the standard model.

Gamma ray spectroscopy will play a similar role for P,T- as for P- violation. The detection of capture gamma rays from the polarized sample is equivalent to the detection of neutrons through the sample and for some design concepts the gamma ray detection might be the most sensitive. The same information about resonance spin and parity and channel spin mixing required for a complete interpretation of P- violation also applies for T-Violation.

3.3 T-Violation in the Strong Force

T-violation has never been observed in the strong force. By measurements of the cross sections for reciprocal reactions such as (p,α) and (α,p) and other means, the sensitivity limit is at the one part in 1000 level [15]. Apparently a much more stringent limit could be placed by resonance transmission of polarized neutrons on an aligned target arranged at a 45 degree angle to the neutron beam [16]. The p-wave resonance must be known to have the wrong spin for exhibiting P-violation. The vector product of interest for T-violation in the strong force is $(\sigma \cdot k \times I)(k \cdot I)$. A statistical accuracy for this experiment of 10^{-6} would allow one to extend the sensitivity for T-violation in the strong force by three orders of magnitude. The experiment also could be done by detecting gamma rays from the aligned sample. Also the required resonance parameters can best be derived by the gamma ray spectroscopic studies.

3.4 Unstable Nuclei

The very high intensity combined with the very low duty cycle available at LANSCE make possible measurements on very small masses of radioactive nuclei. Two experiments are planned which are of strong interest for astrophysics. The first is the study of positron emitters which generally have a positive Q for the (n,p) process. The detector arrangement for these measurements is shown in Fig. 4. The neutron beam is collimated at a flight path of 5.5 meters to a 4 m.m umbra. The sample is a 2 mm spot on a thin aluminum foil. Protons from the (n,p) reaction are detected by a surface barrier detector placed outside of the neutron beam. The neutron flux is monitored by a thin layer of ^6Li which is also deposited on the aluminum foil.

Measurements on samples of ^7Be , ^{22}Na , ^{35}Cl , ^{56}Co , and ^{57}Co are completed or underway. The first results, which were obtained in a few days using a 90 nanogram sample of 53-day ^7Be , are shown in Fig. 5. We were especially pleased that useful measurements were possible up to 10 keV. The primary intent was to improve the accuracy of the low energy cross section, to measure the deviation of the cross section from the $1/v$ dependence, to measure the branching ratio to the ground and first excited states of ^7Li , and to compare with the near threshold measurements of the well studied $^7\text{Li}(p,n)^7\text{Be}$ reaction. The ^7Be data may be applied to the calculation of the primordial nucleosynthesis of ^7Li in the standard hot big-bang model [17]. A resonance suggested by the data of the Dubna group [18] at 200 eV was not observed.

The second experiment on unstable nuclei is the measurement of capture cross sections from thermal to about 30 keV. A 4 π high efficiency 1.5 meter diameter capture tank is being designed which takes advantage of a high bias to detect the summed capture gamma rays in the presence of a high singles rate from the decay of the sample. It appears that measurements of eV resonance capture will be practical for nuclei with half lives as short as 5 days; capture at 30 keV should be practical for half-lives as short as 100 days. It is surprising to find that measurements might be practical on as many as 190 unstable nuclides.

Initially we plan to focus on the measurement of branch-point nuclei in nucleosynthesis [19]. These nuclei are beta emitters; the neutron capture chain reaches a branch point at which beta decay will go in one direction and competing neutron capture will take another. By observing the natural isotope abundances in the mass region, it is possible to determine the neutron flux present in s-process nucleosynthesis. Among the interesting nuclei are ^{115}Cd , ^{148}Pm , ^{152}Eu , ^{154}Eu , and ^{160}Tb .

We have also contemplated an attempt at measuring the capture gamma ray spectrum by placing a Ge-Li detector inside of the tank and close to the sample. The tank would be used in a coincidence arrangement to eliminate background in the Ge-Li detector from the radioactive sample.

Los Alamos is fortunate to have facilities such as the LAMPF beam stop, the OWR reactor, the Ion Beam Facility, isotope separators, and hot cell facilities for sample preparation. Fortunately the sample requirement is so small (between 0.01 and 10 micrograms) that sample handling usually is not a significant problem.

3.5 Neutron Capture Gamma Ray Spectroscopy

It is well known that the familiar resonances of neutron cross sections can exhibit features in their capture gamma-ray spectra atypical of the statistical picture expected from the compound nucleus concept. The best established of these is a mechanism that is described as a valency neutron transition [20] and is closely related to the direct capture process [21] found to be predominate in the thermal cross sections of many light nuclides. However the understanding of these processes is scrappy at present and data in the resonance region is not easily measured. Probably a great deal could be learned if the measurements could be made more quickly and on smaller samples with satisfactory background and resolution conditions.

The source intensity available from a spallation source such as LANSCE exceeds [22] that from the best linacs where these experiments are operational by a factor of 100. This advantage might be substantially greater when due account is taken of the inefficient neutron moderator geometry required at electron linacs to reduce the gamma flash to an acceptable level. In addition there is no gamma flash to degrade the data taken at higher neutron energies. However it is not clear that these advantages put the spallation sources on top for this type of experiment. The linacs have a shorter pulse by a factor of about 25 which allows measurements of a given neutron energy resolution at a shorter flight path. Furthermore the higher repetition rate is generally advantageous from duty cycle arguments.

It is therefore inappropriate to claim that the spallation source will obviously be better than the electron linac for resonance gamma ray spectroscopy. However the present rate of progress in this field is definitely limited by the difficulty of doing these measurements with the sources presently employed. It would be very desirable to evaluate the effectiveness of the spallation source for this work by actual experiments.

3.6 Ultrahigh Resolution Photonuclear Research

The study of individual compound nuclear states in heavy nuclei using gamma-rays is difficult since a monochromatic and variable energy source with the necessary resolution is not available. Some useful work has been possible for lighter nuclei using the threshold photoneutron technique and gamma-rays produced via the (p,gamma) reaction [23]. However, general studies require a resolution of a few eV. Useful intensities for energies of about 7 MeV might be obtained by neutron capture on nuclei with strong transitions to the ground or other low lying states.

Consider the placement of a sample of ^{56}Fe at a flight path distance of 50 meters viewing the moderator on a spallation source. This nucleus exhibits a strong ground state 7646 keV gamma-ray for thermal neutron capture. The thermal capture cross section is 2.59 barns. This cross section behaves approximately as a $1/V$ cross section so that some of strong gamma-rays will be produced for neutrons well into the eV range. The energy of the ground state transition will be $E = E_B + E_n$ where E_B is the binding energy and E_n is the neutron energy. The energy of the gamma-ray therefore will be directly correlated with the energy of the neutron. By placing a sample and an appropriate detector for photonuclear reactions near the gamma-ray source, it might be possible to do ultrahigh resolution photonuclear spectroscopy.

Several factors govern the resolution for this proposed concept; however the most important is the Doppler broadening of the gamma-ray in the emission process. This is about 5 eV for a room temperature mass 100 emitter with an energy of 7 MeV. The resolution in the neutron also contributes. Fig. 6 shows the resolution as a function of neutron capture energy when the approximately constant emission doppler effect is combined with the neutron energy resolution for a flight path of 50 meters. Over much of the energy range the resolution is better than one part per million.

A calculation of the intensity is also shown in Fig. 6. The calculation assumes that a PSR proton current of 100 microamps, a thermal capture cross section for the gamma-ray of one barn, a potential scattering cross section of 10 barns, an ^{56}Fe target thickness in which 10% of the neutrons interact, a flight path of 50 meters, a target area of 100 cm^2 and emission into a full sphere. The result of the calculation is expressed as the integral of the average number of gamma-rays produced per second from 10 eV up to a given higher energy for the conditions described above. For example 2800 photons per second will be produced in the energy range from 10 to 100 eV, which might allow useful experiments.

Possible experiments include photofission on non-thermal neutron fissioning isotopes achieved by detection of fission gamma-rays and/or fission neutrons, photon-induced gamma-ray emission by detecting at least two gamma-rays in a pair of detectors arranged in coincidence, MeV photoneutron emission, or perhaps photoproton emission. These experiments would be complicated by backgrounds from a high proportion of scattered eV energy neutrons. While the impact of this class of experiments is not clear at present, it appears that the intensities could make possible photonuclear experiments with a resolution better than 1 part in 1 million- perhaps the highest resolution nuclear physics experiment performed outside of the Mössbauer effect.

3.7 Neutron-Pumped Gamma-Ray Laser

A gamma-ray laser would combine the special properties of incoherent x- and gamma-rays with the usual features of the laser. It would therefore possess the extraordinary qualities of penetration, ionizing ability, wavelength of interatomic spacing, interaction with electrons in inner shells of atoms, coherence, intensity,

monochromaticity, directionality, reflectivity and focal properties. While the development and application of such a device would be interdisciplinary, almost certainly it would be driven by nuclear processes in the province of low energy nuclear physics. The community represented here probably will play the lead role of devising, building, and first using a gamma-ray laser.

The possibility of using neutron reactions to pump a gamma ray laser has been discouraged through apparently sound general arguments. They can be briefly summarized as requiring neutron intensities which probably can only be produced in a nuclear explosion which would deposit so much energy in the lasing medium that it would be vaporized before lasing could begin [24]. A concept will be described allowing neutron intensity reduction by several orders of magnitude which apparently enables operation at neutron intensities below the vaporization threshold.

Laser action must begin with a nuclear process giving rise to an inversion (more than half the nuclei in an excited state aside from statistical factors). The half-life of the excited state will probably be in the interval from 1 to 1000 nanoseconds. The macroscopic stimulated emission process must be greater than the macroscopic attenuation processes in the laser medium. The stimulated emission cross section can be enhanced into the million barn range by establishing recoilless emission conditions. The attenuation can be greatly reduced by performing isotopic separation of the excited nuclei and subsequent implantation into a favorable host medium in a time short compared to the isomer half-life.

It appears that all this can be achieved by pumping the famous 14.4 keV Mössbauer transition in ^{57}Fe via the $^{57}\text{Co}(n,p)^{57}\text{Fe}$ reaction. The reaction leads to an inversion as shown in Fig. 7. Starting from the $7/2^-$ state of ^{57}Co an s-wave neutron can excite 3-states in ^{58}Co . Angular momentum will restrict the emission of protons to the 136 keV excited state of ^{57}Fe . This state decays with $T_{1/2}$ of 8.6 nanoseconds to the 14.4 keV state 89% of the time creating the inversion.

The recoil from the 1.6 MeV proton emission kicks the ^{57}Fe with an energy of about 25 keV and it will travel about 100 \AA in the ^{57}Co . If the ^{57}Co is distributed in a layer of about this thickness, the ^{57}Fe nucleus will be knocked free and it can be stopped in a second layer of low gamma attenuation and good Mössbauer binding properties such as beryllium or powdered diamond. The range of the ^{57}Fe in these materials is about 250 \AA . Fig. 8 shows a spool of Be foil coated on one side with ^{57}Co . The laser action is parallel to the spool axis. The neutron intensity requirements for lasing are reduced by several thousand by the recoil-based isotopic separation and implantation. Calculations indicate that the gain per centimeter would be high enough to deexcite a substantial fraction of the nuclei in a single pass. The coherence and directionality of the emission however would be poor. These features may be much improved with the addition of mirrors.

Mirrors may be constructed using four single crystals in a diffraction mode arranged [25] as shown in Fig. 8. A high gain per centimeter would compensate for a low reflectivity which might be in the range of only 50% per crystal. Within the 100 nanosecond half-life, the light would travel about 30 meters allowing time for many circuits and thereby greatly improving the laser efficiency and the coherence and emittance of the beam.

The performance of this system is based on estimates of the (n,p) cross section in the eV and lower keV range. The most likely possibility is a resonance at about 400 eV with a peak (n,p) cross section of about 300 barns and a width of about 7 eV. Hopefully (n,p) measurements will be completed on this nucleus at LANSCE this fall. Measurements made at the OWR reactor in the thermal range give a cross

section [26] twice as large as that expected if all of it were associated with the low energy wing of the proposed resonance. The density of excited nuclei required for this concept is reduced by six orders of magnitude below that required in ^{57}Fe without nuclear transmutation, isotopic separation, and implantation. In addition, the expected size and position of the resonance is favorable for the inversion dynamics. At the reduced neutron intensity, the lasing medium should survive the pumping process.

Perhaps we have been overly pessimistic about the prospects for the gamma-ray laser. The favorable cross-section and rapid implantation technique have led me to reconsider the feasibility of two-step gamma-ray lasers. Most schemes presently being studied, including those under investigation elsewhere at Los Alamos, are three-step lasers, in which an isomeric storage level is excited, the isomer implanted in a host, and finally the lasing level populated by some kind of transfer radiation. Admittedly, serendipity is involved in making this particular concept for flux reduction possible. However, there may be many pumping schemes which might be identified by appropriate spectroscopic studies on low lying states of promising nuclei. A laboratory source of coherent gamma-rays would be a truly exciting development both for low energy nuclear physics and for many other research fields as well.

3.8 Other Neutron Physics Research

The above research topics have a rather direct tie to neutron gamma-ray spectroscopy. However the spallation sources make possible other neutron nuclear physics experiments as well. In addition there are non-nuclear physics experiments at the interface between nuclear and condensed matter physics. Also there are condensed matter experiments which operate in an energy range uncommonly exploited in condensed matter physics or which use techniques developed and well understood by neutron nuclear physicists. The strong involvement of nuclear physicists in the latter classes of experiments might well result in more rapid exploitation of these fields. A few of the experiments falling into these classes will now be briefly described.

3.8.1 Neutron-induced Electronic Excitation

Electronic excitation in atoms and molecules via neutron-induced reactions can occur by three mechanisms. The first is the much discussed interaction of the magnetic moments of the neutron and the electron [27]. One is interested in eV incoming neutron energies and in electronic excitations of a few eV with small momentum transfer and excellent energy resolution (1/1000). The second [28] is excitation arising from recoil of the nucleus under the electron cloud in a high momentum transfer neutron-nucleus interaction. The third [28] is another high momentum transfer excitation arising from non adiabatic coupling (NAC) between the nuclei in a diatomic or more complex molecule. Background could be significantly reduced by detecting the decay photon following electronic excitation in coincidence with the scattered neutron. For the NAC interaction, the selection rules are substantially different from electromagnetic selection rules and more restrictive so that the spectrum might be less complex and therefore more easily resolved and interpreted.

3.8.2 Physics of Neutron Dosimetry

In contrast to biological damage arising from gamma-rays, which is primarily dependent on the deposited ionization energy density, the damage from neutrons is probably dependent on heavy atom displacements. For neutrons in the 0.01 to 1000 eV range there are probably four damage mechanisms of interest [1]. A measure of

the inelastic neutron spectra in this energy range using an intense pulsed neutron source might suggest or demonstrate low damage effects by neutrons.

3.8.3 Resonance Neutron Optics

The wave properties of neutrons give rise to optical properties which are well established for thermal energies. These properties are usually expressed through an index of refraction $n = 1 - \lambda^2 p a_{\text{coh}}/2$ where λ is the wavelength of the neutron, p is the density of nuclei, and a_{coh} is the real component of the coherent neutron scattering length. For higher energy neutrons the strong wavelength dependence results in a value for n very close to unity except at resonances where the scattering length can become quite large compared to that at thermal energies- thereby compensating for the shorter wave length. At resonance it is probably possible to observe resonance total reflection and perhaps even neutron focusing with long focal length lenses. The large resonance scattering length also should allow enhanced diffraction effects at resonances which should be observable in powder and single crystal diffraction studies. While these are now primarily of academic interest, some application might be made for neutron beam handling and in spectroscopy of low energy neutrons without resorting to neutron time-of-flight techniques.

3.8.4 Resonance Neutron Radiography

This technique [29] makes use of the strong neutron resonances in nuclei for nondestructive diagnostic purposes. Transmission measurements conducted using time-of-flight techniques allow the quantitative determination of the isotopic content of an object. The use of two-dimensional position-sensitive neutron detectors with resolution as good as 300 microns also allows a measurement of the position distribution of particular isotopes of interest. In some situations the technique might be enhanced by the application of gamma-ray spectroscopy. The new high intensity sources and high data collection techniques will enhance the effectiveness of this method.

3.8.5 Lead Slowing-down Spectrometer for Ultra-high Intensity

The lead slowing down spectrometer [30] is a means of creating a very high intensity source for poor resolution neutron spectrometry using the time correlation of the neutrons in a 1 m³ lead assembly. The PSR could inject 10^{15} n/burst into the assembly which is probably three orders of magnitude more neutrons than have been used previously. Since the sensitivity gain of this instrument is about 10^4 times that of a comparable neutron time-of-flight experiment, the sensitivity for cross section measurements would be extraordinary for experiments where poor resolution is acceptable.

3.8.6 Neutron-neutron Scattering

The neutron-neutron scattering length has never been directly measured and its value to an accuracy of a few percent is of great interest. Experiments on the edge of practicality have been proposed for steady state thermal neutron sources. Since the n-n scattering length depends on the square of the neutron flux, the spallation pulsed source has a decided advantage over the steady state reactor. A cavity can be built containing a gas of thermal neutrons which is viewed by a detector through a collimated path which does not allow the detector to see the cavity walls. If the cavity is filled with a low density of hydrogen gas, the n-p scattering will be proportional to the first power of the flux. Therefore by measuring the scattering rate as a function of peak flux in the cavity, the n-n rate can be separated from the n-p rate and the n-n scattering length measured relative to the n-p scattering length.

Although a calculation has not been done for a spallation source, it has been done for a pulsed reactor [31]. For a flux of 10^{17} n/cm²-sec, a cavity 10 cm long and 10 cm in radius, a detector distance of 12 meters, a detector radius of 10 cm and a pulse width of 6 milliseconds, the detected rate is 30 neutrons per pulse.

4. CONCLUSIONS

The power of these sources for neutron nuclear physics is truly exciting for the lower energy range and complementary capabilities also can be readily implemented for forefront work in the MeV range. I urge the community represented here to become actively involved in physics at these sources. As an incentive I wish to remind you that neutron physics is always intensity limited. However the rate of advance in intensity is truly astounding as shown in Fig. 9. The intensity increase has been almost two orders of magnitude per decade for the past 35 years and there is no technological barrier against this continuing for some time. Neutron experimenter's which you considered and rejected years ago might now be easy.

We nuclear physicists should salute the neutron scattering community for their role in continuing the advance in source intensity, and we should work cooperatively to assure the full exploitation of all the science made accessible by these new facilities.

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Figure Captions

Fig.1 The Los Alamos Epithermal and White Sources based at LAMPF. As described in the text, 10% of the LAMPF beam is directed to the Proton Storage Ring which compresses the beam into 0.27-microsecond pulses and feeds them to LANSCE (Target 1). A small amount of H^- beam is accelerated simultaneously on most LAMPF pulses along with the proton beam. These beams are separated at the end of the accelerator and the low current H^- beam bypasses the PSR on the way to the MeV White Source (Target 4).

Fig. 2 The resolution at LANSCE for path lengths of 7, 50, and 250 meters is read from the ordinate on the left. The polarization expected this fall using the polarized 3He is given referring to the ordinate on the right.

Fig. 3 Plan view of the Los Alamos P-violation experiment. Neutrons travel through seven meters of biological shielding and collimation to the first La_2O_3 sample. The beam transmitted through the sample is weakly longitudinally polarized near the 0.734 eV resonance. The beam then travels through three sets of coils, which make up the spin flipper, to the second sample and are detected in a 6Li -glass detector.

Fig. 4 Apparatus for low energy (n,p) measurements. A collimated neutron beam emerges from the right and strikes a sample mounted on a thin aluminum foil adjusted in position from the bottom. A surface barrier detector adjusted from above detects the charged particles.

Fig. 5 The $^7Be(n,p)^7Li$ cross section measured at LANSCE and compared with an R-matrix fit obtained from a number of reactions proceeding through the 8Be system.

Fig. 6 Intensity and resolution for ultrahigh resolution ($< 1/10^6$) photoneuclear experiments using 7.646 MeV gamma-rays derived from variable energy eV neutron capture in ^{56}Fe . The left ordinate shows the integral of the number of gamma rays produced per second by neutrons with energies between 10 eV and a higher energy given on the abscissa. The ordinate on the right shows the resolution of the gamma-ray in eV.

Fig. 7 The $^{57}Co(n,p)^{57}Fe$ reaction producing a population inversion for the 14.4 keV gamma-ray in ^{57}Fe . For $l = 0$ neutrons only the 3^- states reached in ^{58}Co can decay with appreciable amplitude by proton emission to ^{57}Fe . Of the possible ^{57}Fe states only the 136 keV state can be reached by $l = 0$ protons. It decays 89% of the time to the 14.4 keV state producing the inversion.

Fig. 8 Geometry for the gamma-ray laser. A 0.005-cm thick Be foil is coated on both sides with a 100-A thick layer of ^{57}Co . A thin 250-A thick layer of Be is then deposited on the cobalt on one side. A cylinder is then wound as shown in a. The cross section across the cylinder is shown in b; stimulated emission is directed vertically. The four-mirror arrangement shown in c improves the emittance and the efficiency.

Fig. 9 The advance of spallation neutron source intensity for the production of epithermal neutrons. The intensity is the total neutron production averaged over one second.

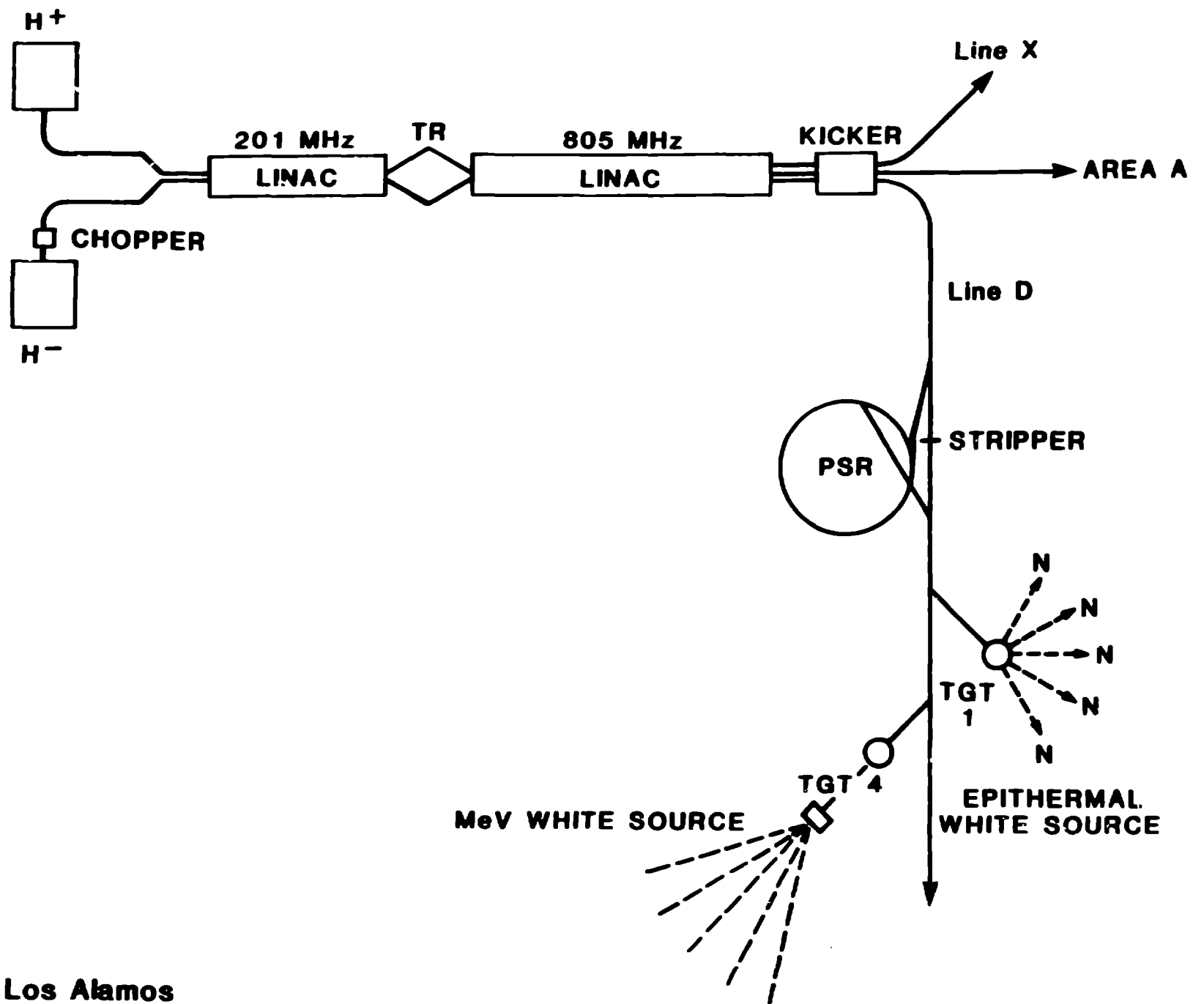


Fig. 1

Los Alamos

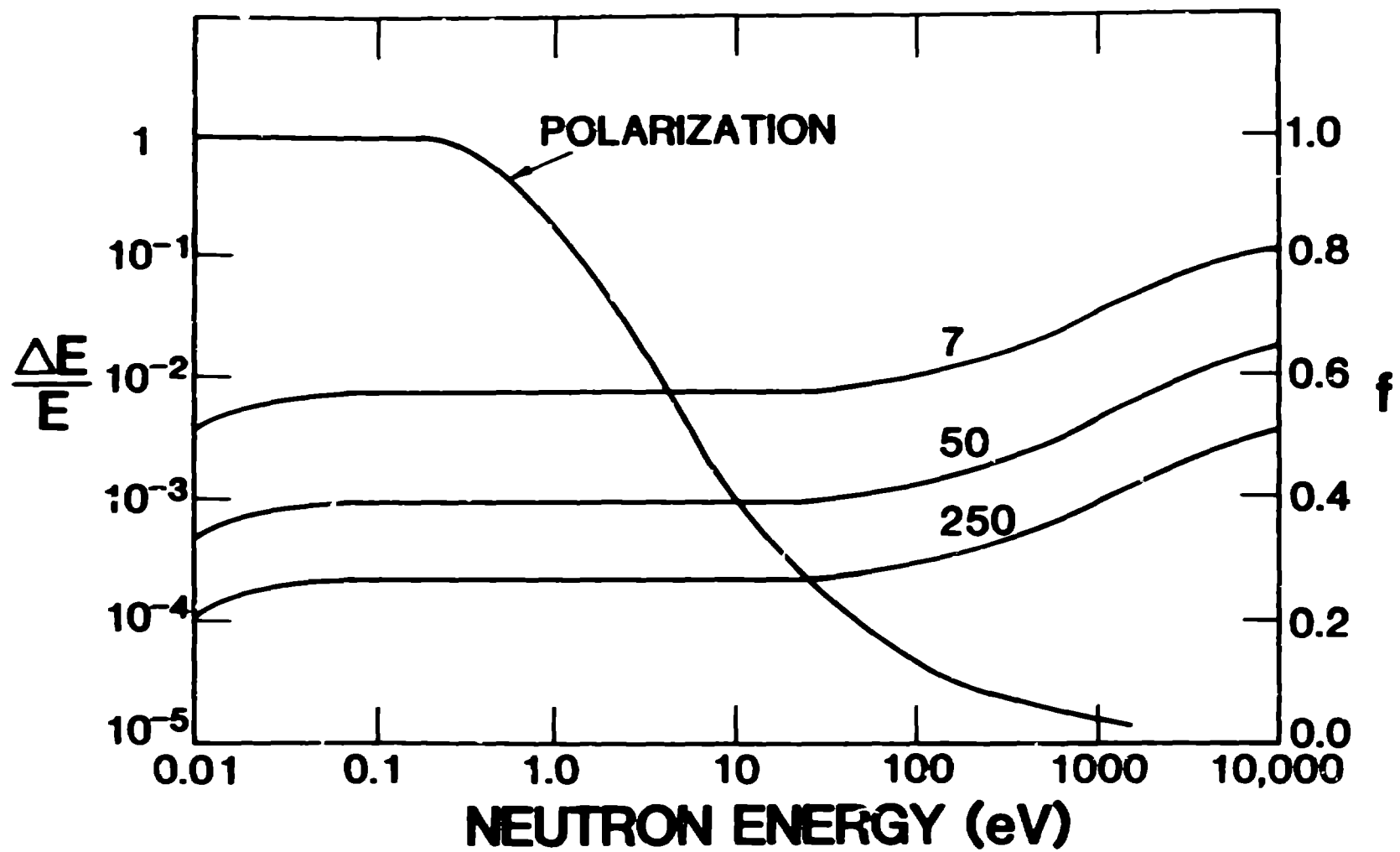


Fig. 2

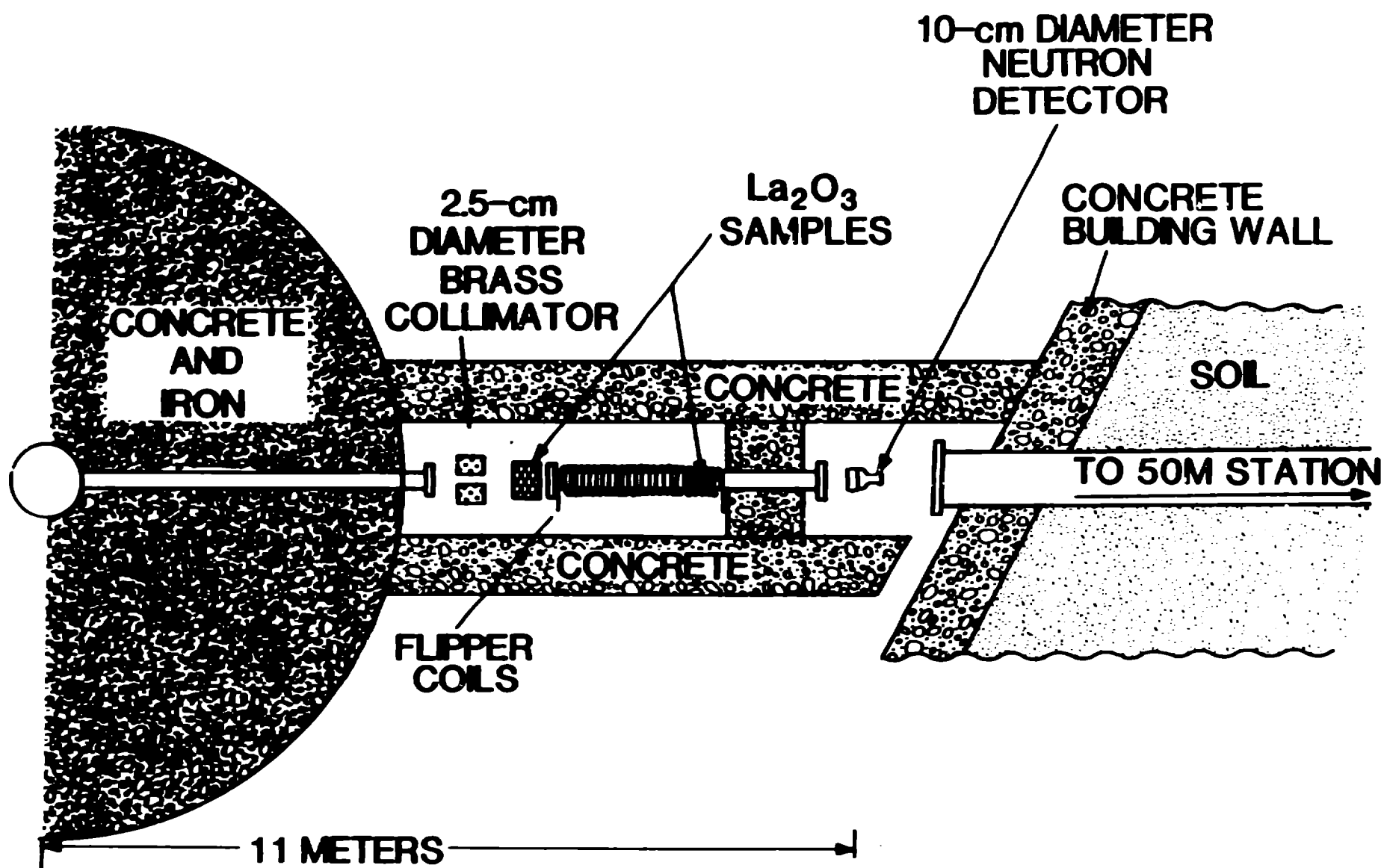


Fig. 3

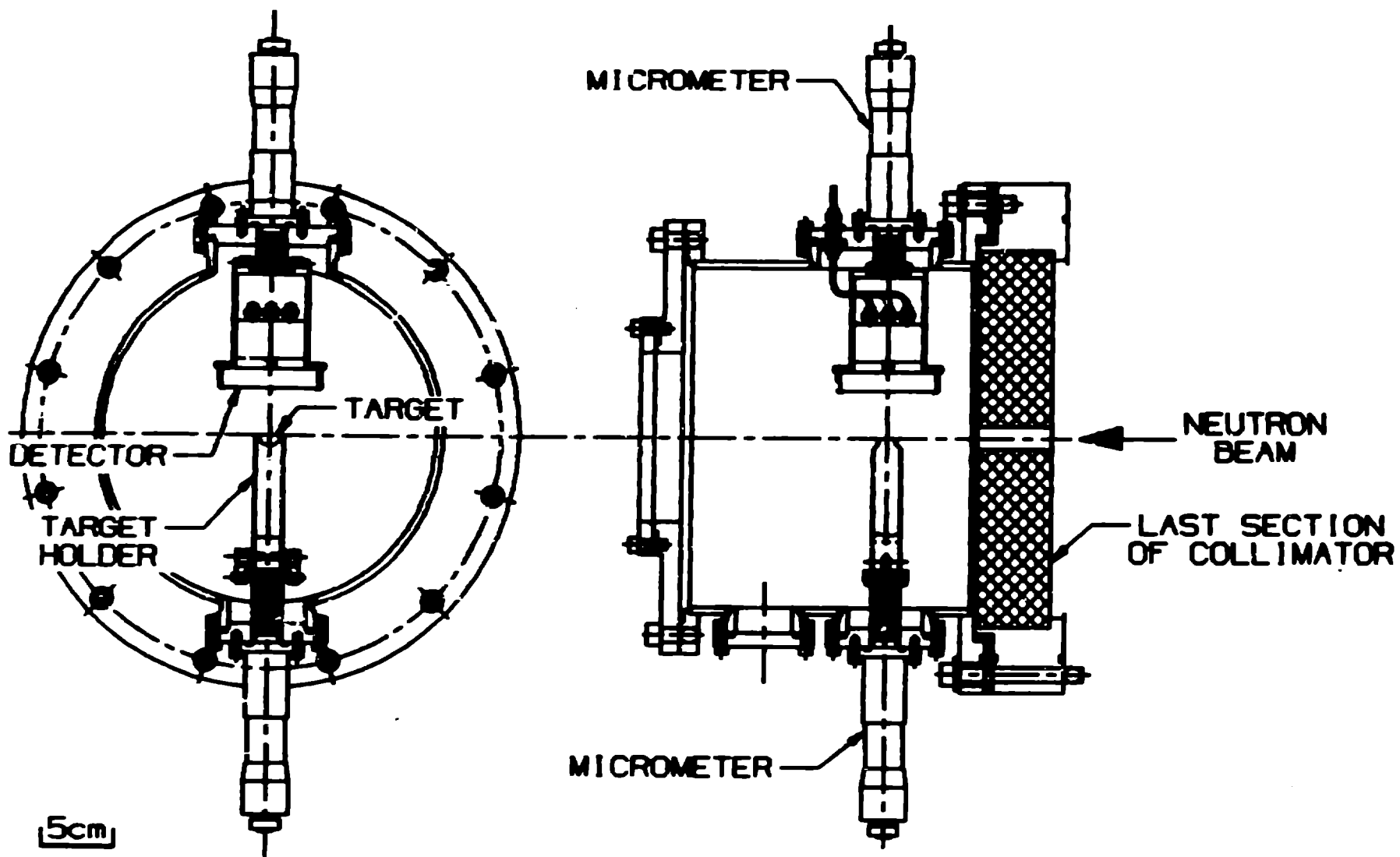


Fig. 4

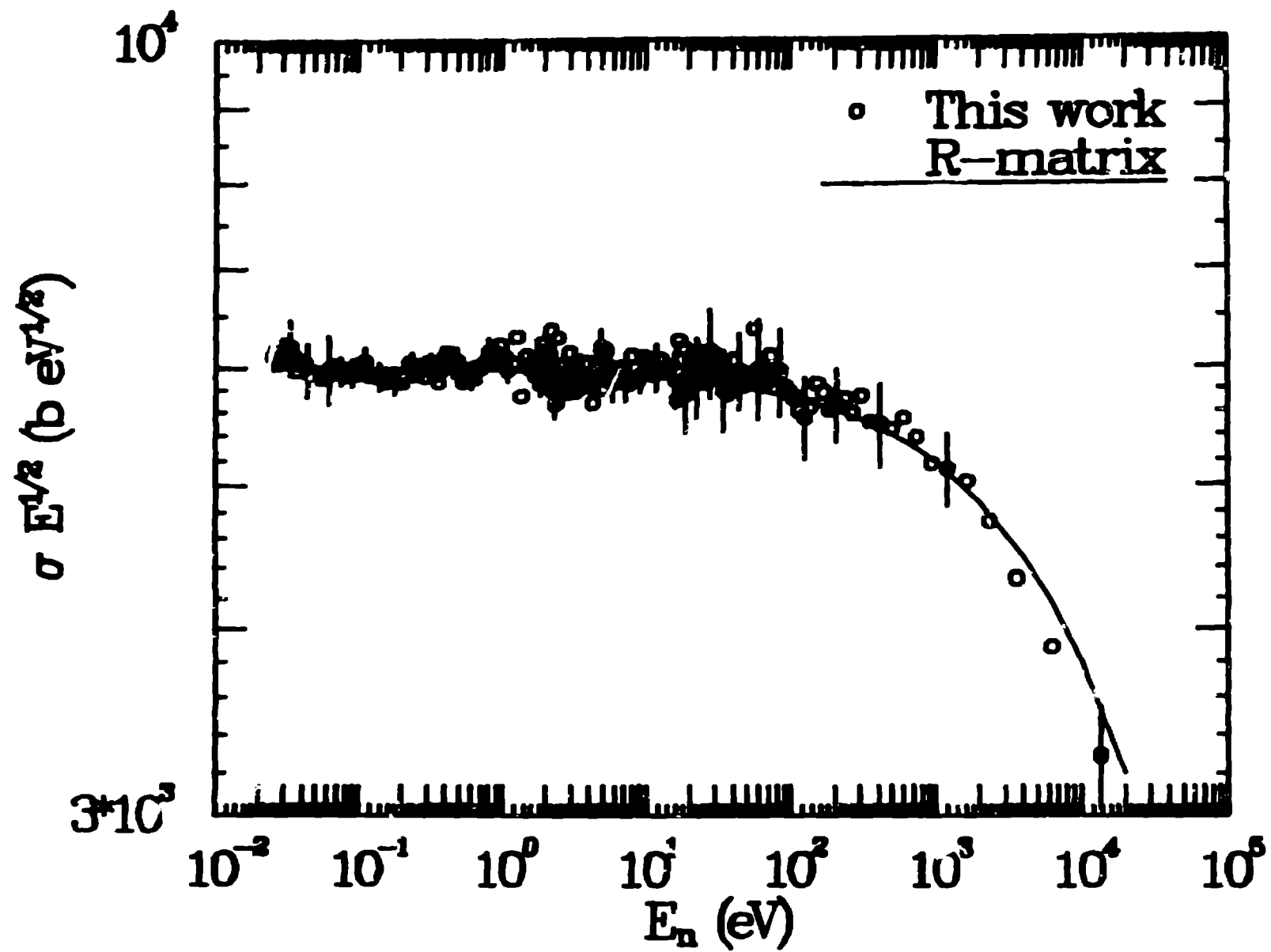
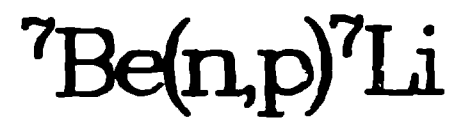


Fig. 5

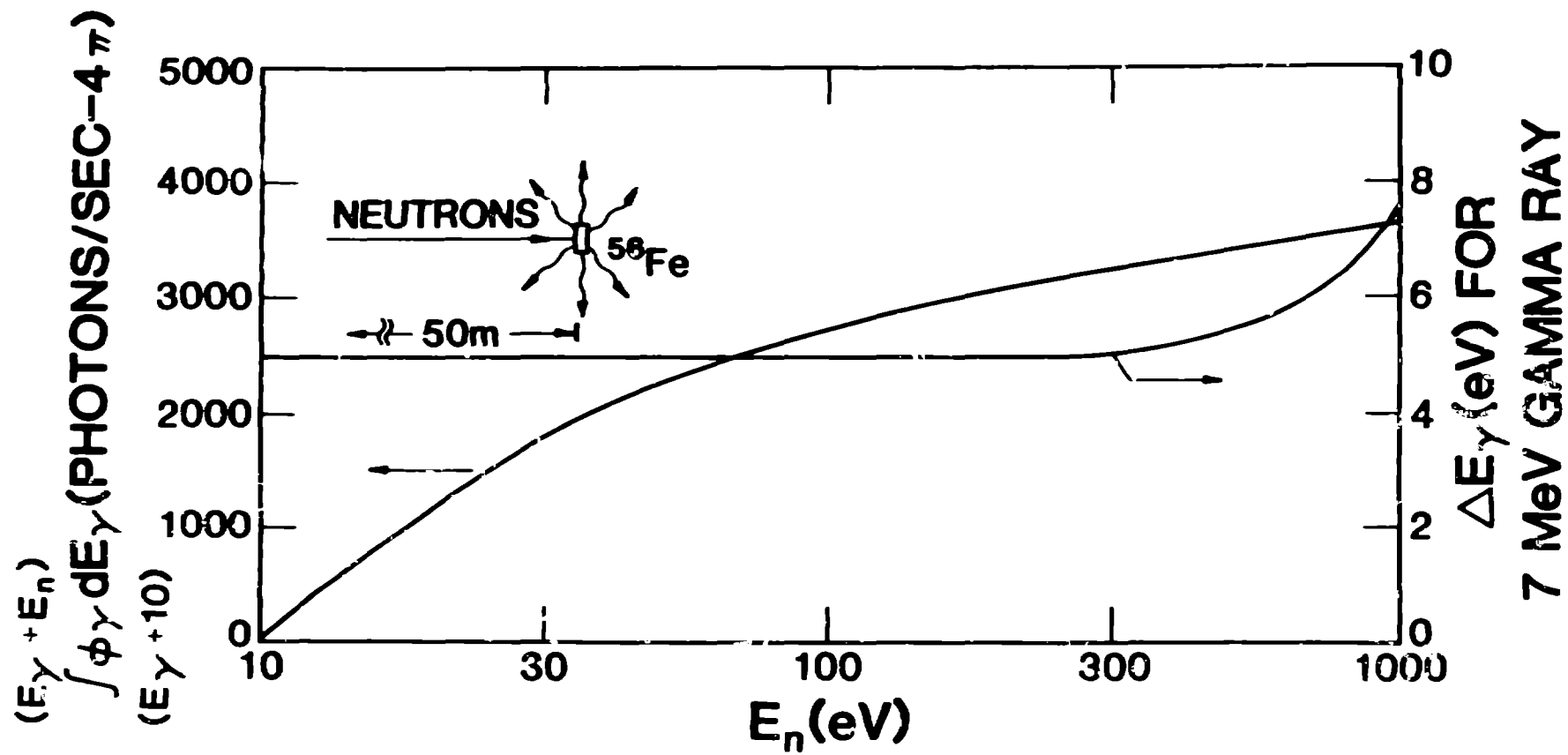


Fig. 6

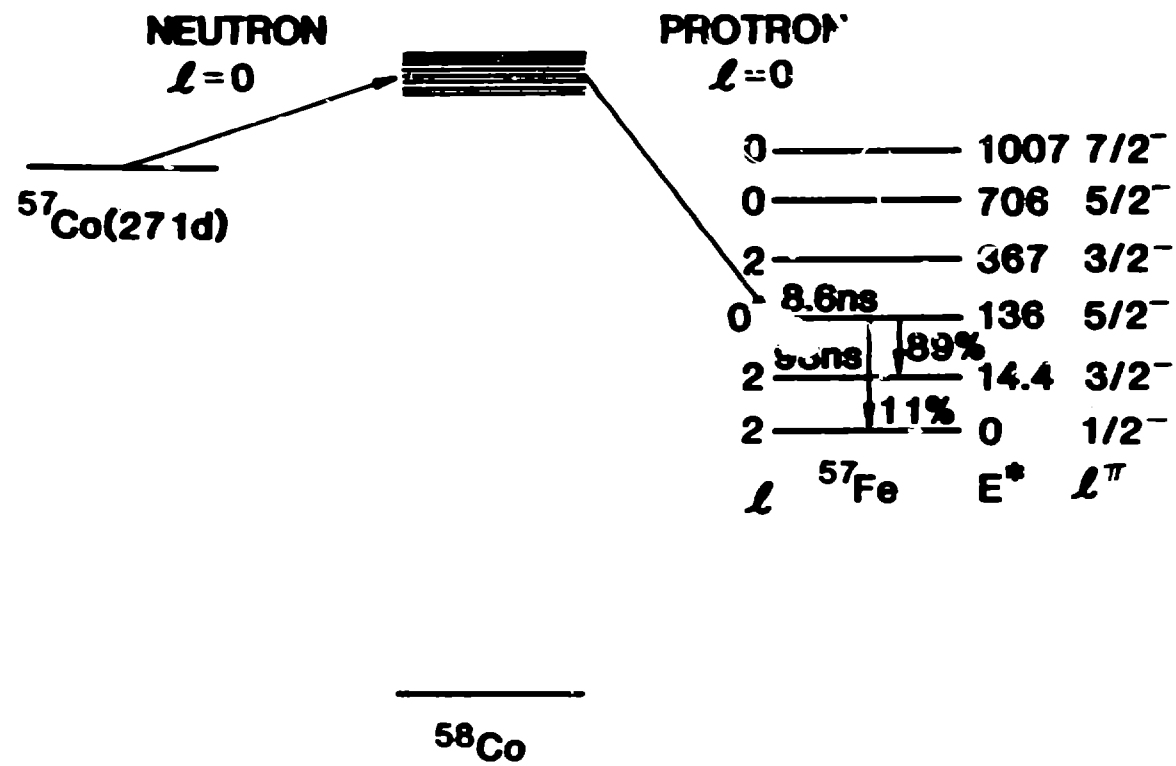
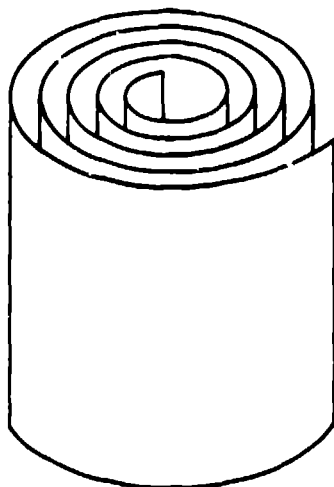
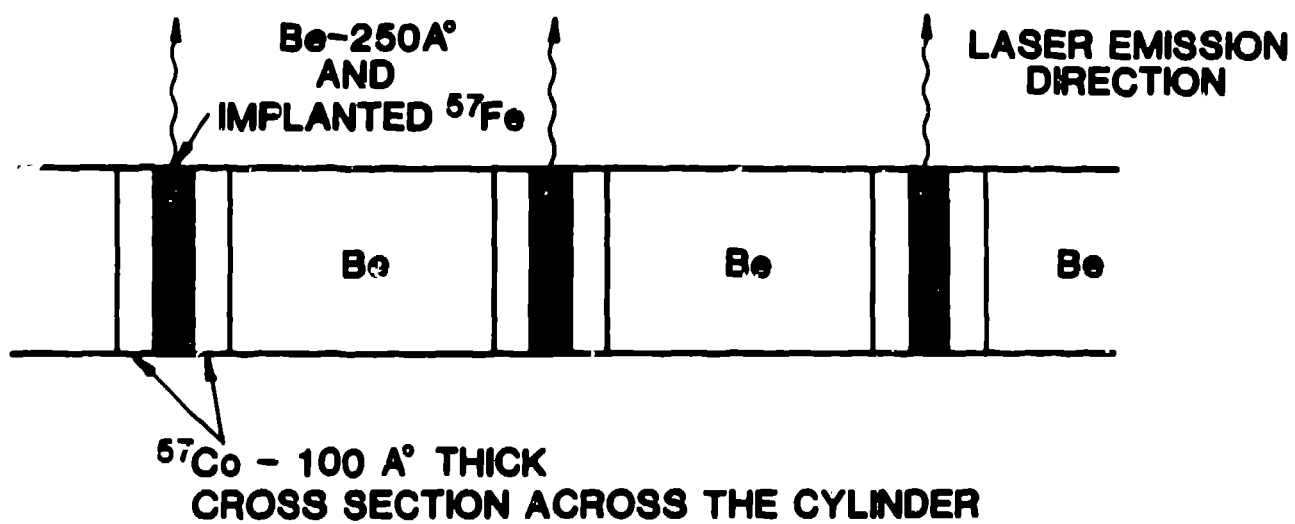


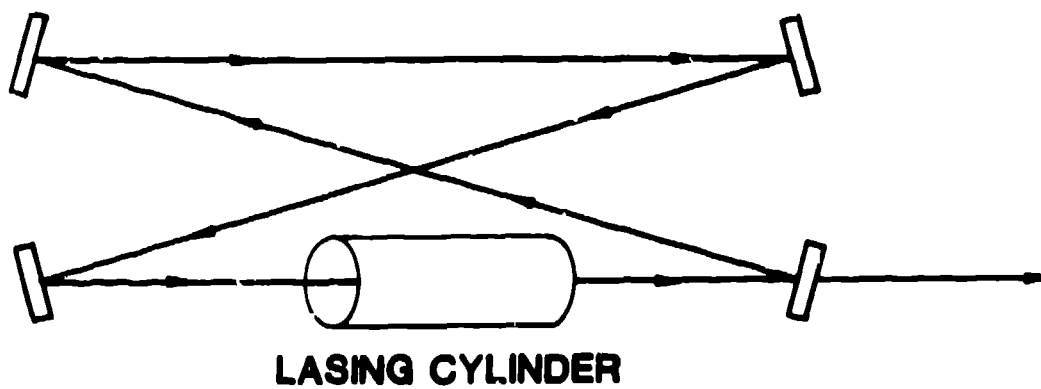
Fig. 7



(a)



(b)



(c)

Fig. 9

